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WAVELET TRANSFORMATIONS FOR HELICOPTER IDENTIFICATION VIA ACOUSTIC SIGNATURES

BY JEFFREY L. SOLKA CAREY E. PRIEBE
HALFORD I. HAYES GEORGE W. ROGERS
SYSTEMS RESEARCH AND TECHNOLOGY DEPARTMENT

MAY 1994

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FOREWORD

The role that the wavelet transformation might play in the identification of helicopters from their acoustic signals is explored in this document. The utility of using a feature extraction system employing both conventional Fourier transform techniques in combination with the wavelet transform is discussed. Depending on the nature of the mission, such a system could either improve the helicopter identification process by suppressing transient noise prior to feature extraction using conventional techniques or provide the opportunity to use transient signatures to identify a specific helicopter in a group consisting of homogenous model types.

This work was done in support of the Advanced Processors for Weapons Sensor Fusion program of the U. S. Marine Corps and has been conducted in the Advanced Computation Technology Group of the Systems Research and Technology Department.

This report has been reviewed by Dr. Richard A. Lorey, Head, Advanced Computation Technology Group.

Approved by:

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D. B. COLBY, Head
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ABSTRACT

The ability to classify helicopters based on their acoustic signature has applications to both detection and tracking. The current approach to this problem uses standard signal-processing techniques to extract features based on the fundamental harmonics of the helicopters' blades. This document examines the role that the wavelet transformation might play in this feature extraction process. It addresses ways to use the wavelet transform both to improve the performance of the existing approach and to expand the capabilities of the classification system.

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INTRODUCTION: HELICOPTER IDENTIFICATION PROBLEM

The problem of interest here is the classification and tracking of helicopters from their acoustic signatures. These tasks are to take place under field conditions. The timeline requirement for these tasks is as close to real-time as possible.

There are several things that act to complicate this problem. First, there is the existence of transient battlefield signals such as gunshots, explosions, etc. Second, there are periodic processes that are part of the environment. These include generator noise and friendly craft signatures. The final factor is that there are usually several crafts' signals acting in concert with one another. These factors act either to degrade the signal of interest or to introduce artifacts into the signal that compromise the classification and tracking mission.

Current approaches to this problem use spectral analysis techniques to extract the fundamental frequencies of the main and tail rotor of the craft. A classification signature is formed using the ratio of these frequencies. Recent work by Poston[1] et al. has employed harmogram analysis to extract these frequencies.

This document examines the use of the wavelet transformation (WT) as an alternate approach to this feature extraction problem. Feature extraction schemes that only use the WT and hybrid wavelet transformation/fast Fourier transform (WT/FFT) schemes are discussed within. The use of the WT to circumvent some of the above mentioned problems is also discussed.

This document begins with a brief review of the mathematical underpinnings of the WT, including discussions of both continuous and discrete WT. With this background in hand, the application of the WT to signal processing will be considered with specific attention to the helicopter problem. These discussions include some information about available hardware for real-time implementation of the WT. This document concludes with recommendations for future work.

WAVELET TRANSFORMATION

As a starting point for the introduction to the WT, the concept of Fourier series expansion will be reviewed briefly. In Fourier series expansion, the sine and cosine functions are used at different frequencies as a basis for the space $L^2(R)$ of square integrable functions. This basis is very useful for decomposing functions of a periodic nature; i.e., those functions that are localized in frequency space.

The basis functions used in the WT are dialations and translations of a single function known as the mother wavelet Ψ. The kth order transtation of Ψ at a resolution of order j is given by

$$\psi_{jk}(x) = \sqrt{2^{-j}}\psi(2^{-j}x - k) \tag{1}$$

Given certain properties on this mother wavelet, the Ψ_{jk}'s form an orthonormal basis of $L^2(R)$.

A classical example of such a mother wavelet is the Haar function $\psi(x) = 1$, if $0 \leq x \leq 1/2$, -1, if $1/2 \leq x \leq 1$, and 0 otherwise (see Figure 1). The Haar function is a good example of how simple a mother wavelet can be. The wavelets that are used within this document are smoother generalizations of the Haar wavelet.

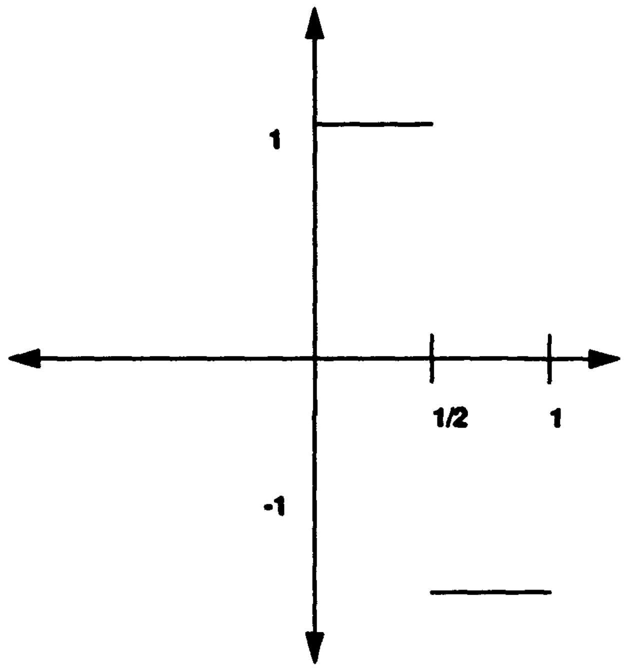

FIGURE 1. HAAR MOTHER WAVELET

For the purposes of this mathematical development, discussions will be limited to the one-dimensional WT. The inner product of f(x) with g(x) is written as

$$\langle g(u), f(u) \rangle = \int_{-\infty}^{\infty} g(u) f(u)\, du \tag{2}$$

Before the implementation details of the discrete wavelet transform (DWT) are discussed, some background on the continuous wavelet transform is appropriate. Given a function f(x), the goal is to expand the function in the wavelet basis. One desires to write

$$f(x) = \sum_{jk} d_{jk}\Psi(x) \tag{3}$$

where the expansion coefficients are given by

$$d_{jk} = \langle f(x), \psi_{jk} \rangle \tag{4}$$

In the DWT case, one starts with a data set $S^0 = \{x^0{}_1, x^0{}_2, ..., x^0{}_N\}$ where N is a power of 2. This discussion of the DWT will be based on the multiresolution approach of Mallat. In this approach, one starts with a blurring function φ that along with its dialations and translations φjk spans the space of multiresolution approximations of the original function. This φ, in turn, induces a wavelet ψ and basis ψjk. These φjk and ψjk act together to span the space of $L^2(R)$. The blurring function for the Haar wavelet is just the characteristic function on [0,1], i.e. $\chi(x) = 1$ if $x \in [0, 1]$ and $= 0$ otherwise (see Figure 2).

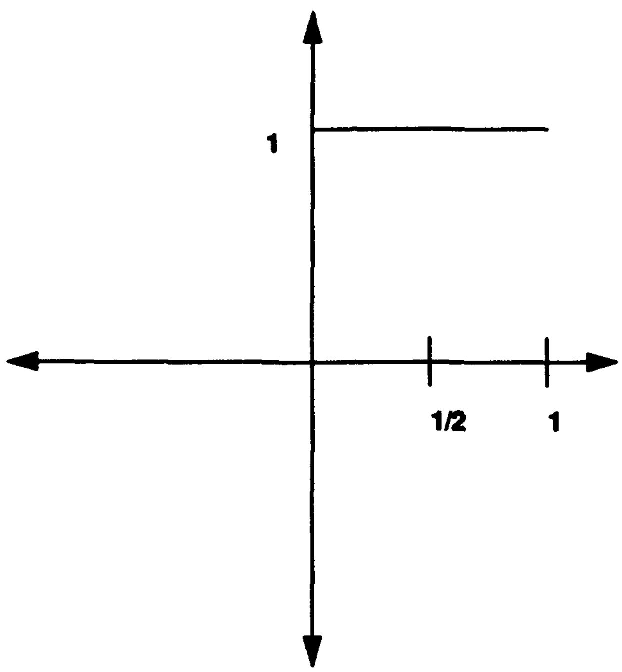

FIGURE 2. BLURRING FUNCTION CORRESPONDING TO HAAR MOTHER WAVELET

In this manner, the original signal at a resolution of 2^0 is split into a direct sum of a multiresolution approximation at a level of 2^{-1} (obtained using the appropriate ϕjk's) and a detail signal (or set of wavelet coefficients) is obtained using the appropriate ψ_{jk}'s. Therefore, one symbolically writes

$$S^{2^0} = S^{2^{-1}} \oplus D^{2^{-1}} \tag{5}$$

where $D^{2^{-1}}$ is the detail signal at a resolution of 2^{-1}. In some sense, $S^{2^{-1}}$ can be though of as the best approximation at a resolution level of 2^{-1} of the original signal and $D^{2^{-1}}$ is the set of details

that are lost in going from $S^{2^{0}}$ to $S^{2^{-1}}$. This process can be repeated using the multiresolution approximation to the signal at the level of 2^{-1} as the starting point. This leads to

$$S^{2^{-1}} = S^{2^{-2}} \oplus D^{2^{-2}} \tag{6}$$

which is analogous to Equation 5. Finally we may combine these equations together to write

$$S^{2^{0}} = (S^{2^{-2}} \oplus D^{2^{-2}}) \oplus D^{2^{-1}} \tag{7}$$

In this manner, the signal is reconstructed from its set of wavelet coefficients and lowest level multiresolution approximation.

An inherent drawback to the Haar wavelet is its lack of smoothness. This problem has been addressed by Daubechies[3] and others by taking convolution powers of the Haar mother wavelet. The graphs of the N=2 second-order convolution powers for the blurring function and the mother wavelet are given in Figures 3 and 4.

By varying N, one can obtain different blurring functions N^{Φ} and wavelet functions N^{Ψ}. The smoothness of these functions increases as N is allowed to increase. For a delightful introduction to the creation of wavelet bases, see the recent paper of Strichartz.[4]

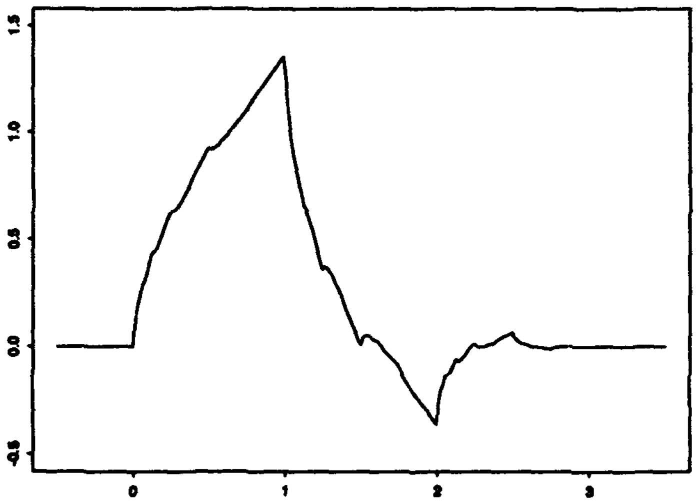

FIGURE 3. GRAPH OF DAUBECHIES COMPACTLY SUPPORTED BLURRING FUNCTION 2^{Φ}

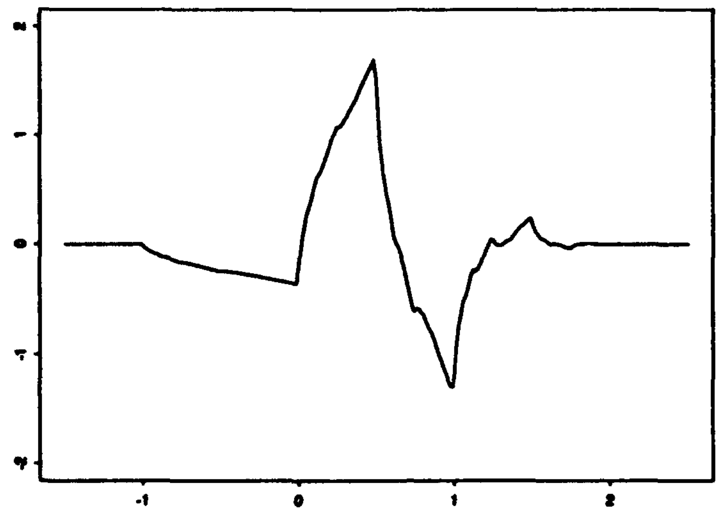

FIGURE 4. GRAPH OF DAUBECHIES COMPACTLY SUPPORTED MOTHER WAVELET FUNCTION 2^{Ψ}

RESULTS

In this section, some preliminary classification results are presented. These results were obtained using field collected signals from two different helicopter models. Ultimately, the fielded system must possess the ability to distinguish between several different models, but this proof of concept study only addresses the two-class problem.

The two helicopter signals are designated 110 and 117. The signals were collected at 2000 Hz. The time domain representation for approximately 2 sec (4096 samples) of signal data is given in Figure 5.

The dyadic Daubechies N=2 wavelet transform of each of the two signals is given in Figures 6 and 7. The coefficients are plotted bottom to top from a resolution level of 2^{-1} = 2048 values to a resolution level of 2^{-11} = 2 values. The decision to use the N=2 mother-wavelet for the subsequent discriminant analysis was made somewhat arbitrarily. Figure 8 shows the histogram for the two helicopters.

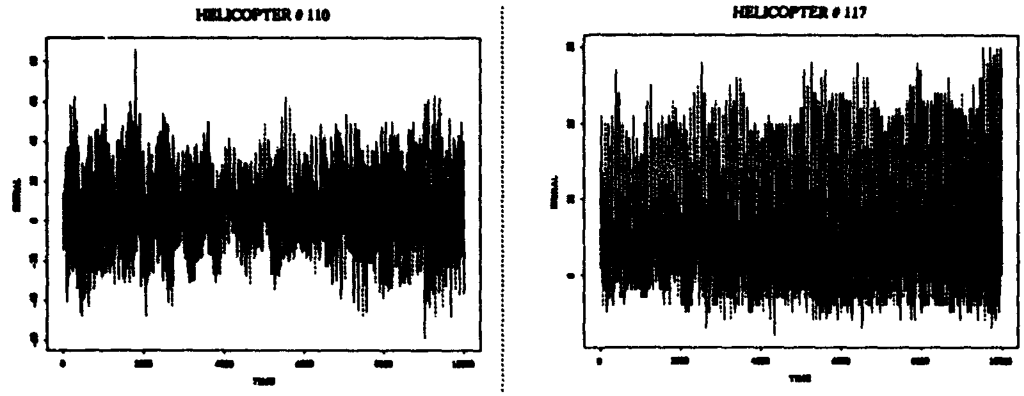

FIGURE 5. TIME DOMAIN PLOT OF TWO SIGNALS

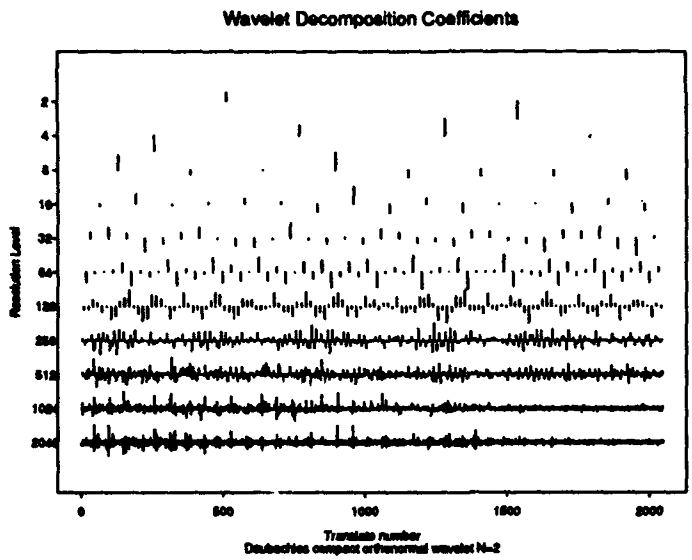

FIGURE 6. WAVELET TRANSFORM FOR HELICOPTER 110

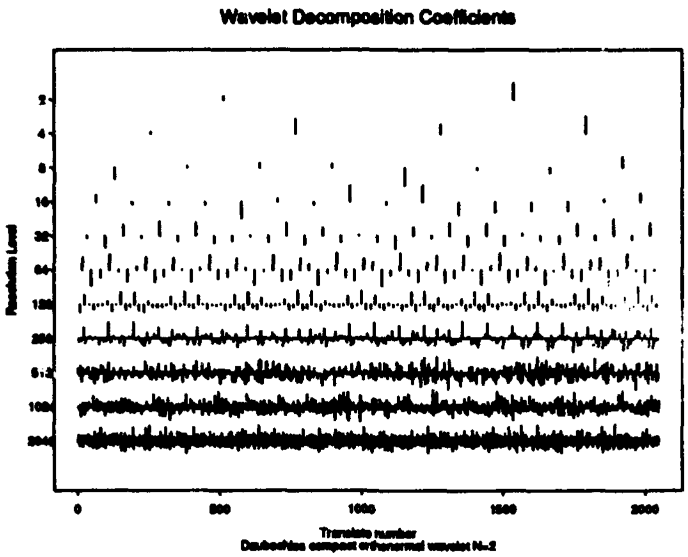

FIGURE 7. WAVELET TRANSFORM FOR HELICOPTER 117

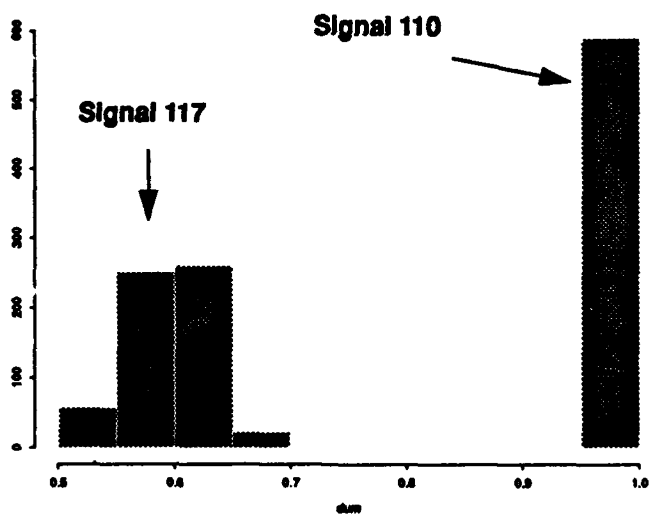

FIGURE 8. HISTOGRAM OF FEATURES AT RESOLUTION LEVEL OF 2^{-5} FOR TWO HELICOPTERS

Given this set of coefficients, one is faced with the daunting task of extracting an appropriate set of features from them. The curse of dimensionality and common sense prevents one from conducting discriminant analysis in R^{4095}. With this end in mind, the following procedure was used.

Given $D^l = \{d^l_1, d^l_2, \ldots, d^l_{2^{12+l}}\}$, the set of wavelet coefficients at level 2^l, the energy E^l at this resolution level can be estimated using

$$E^l \propto \sum_{i=1}^{2^{l+12}} (d_i^l)^2 \tag{8}$$

The set of 12 values $\{E^0, E^1, \ldots, E^{11}\}$ was then normalized by using a standard linear transformation to map the largest value to 1 and the smallest value to 0. The sampling window was then shifted 10 units to the right, and the process was repeated. In this manner, 591 twelve-dimensional data points were generated for each of the two signals.

These data will now be analyzed. Table 1 contains the first two feature vectors for each class. One notices that the maximum energy concentration occurs at a different resolution level for the two classes. In particular, Signal 110 obtains its maximum at a resolution level of 2^{-5}, while Signal 117's maximum occurs at level 2^{-6}. It would be very fortuitous from a discriminant analysis perspective if this trend persisted throughout the signal duration. In fact, the signals studied indicate this trend is consistent throughout the duration of the signal. The histogram of Figure 8 illustrates that there is no overlap between the histograms of the level 2^{-5} feature for 110 and 117. In fact, as with the first two examples, the value holds constant at 1; i.e., the maximum energy for Signal 110 consistently occurs at a resolution level of 2^{-5}.

TABLE 1. FIRST TWO FEATURE VECTORS FOR EACH CLASS

Level	110-1	110-2	117-1	117-2
2^{-12}	0.000	0.001	0.000	0.002
2^{-11}	0.004	0.000	0.000	0.000
2^{-10}	0.024	0.006	0.012	0.015
2^{-9}	0.253	0.283	0.011	0.011
2^{-8}	0.109	0.071	0.049	0.049
2^{-7}	0.137	0.120	0.060	0.057
2^{-6}	0.344	0.340	1.000	1.000
2^{-5}	1.000	1.000	0.617	0.607
2^{-4}	0.596	0.613	0.296	0.271
2^{-3}	0.161	0.137	0.118	0.126
2^{-2}	0.106	0.104	0.093	0.085
2^{-1}	0.111	0.101	0.131	0.129

It is certainly appropriate at this point to elaborate on the significance of this phenomena and to try to provide some explanation of the underlying mechanism that produces it. Note that perfect classification results can be obtained using the features of Figure 8. A P(CC)=1.0 can be obtained with a corresponding P(FA)=0.0 using a simple threshold between the two distributions, which clearly demonstrates the utility of this feature.

Given the periodic nature of the signals, it is possible for the energy to be partially concentrated at a particular resolution level. Similarly, the presence of transients in the signal can be manifested by energy concentration at a certain resolution level. The phenomena seen may be a combination of these two effects. If the concentration is solely frequency based, then this signature may be useless in distinguishing between two of the same models or between any two signals with similar frequency components. The utility of the signature is greatly enhanced if it is based on transients in the signal.

A capability of the WT that has not been discussed is noise/transient suppression. Given a signal that has been corrupted by some sort of stochastic process, it is possible to decompose the signal in a wavelet basis and then reconstruct the signal with the noise suppressed. The results section concludes with an illustration of this capability. The original signal f(x)=sin(x) + N(0,1) is displayed in Figure 9. The wavelet coefficients for a Daubechies wavelet N = 8 is plotted in Figure 10.

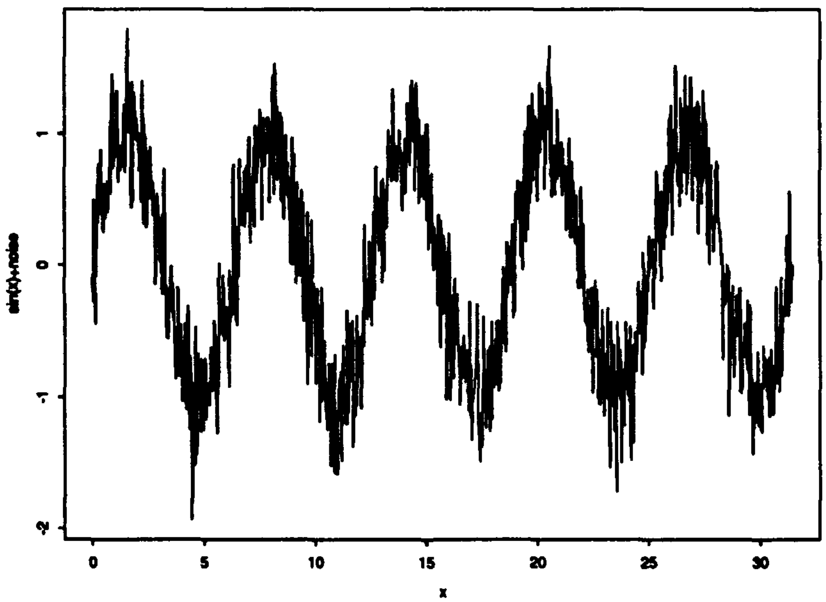

FIGURE 9. f(x) = sin(x) + N(0,1)

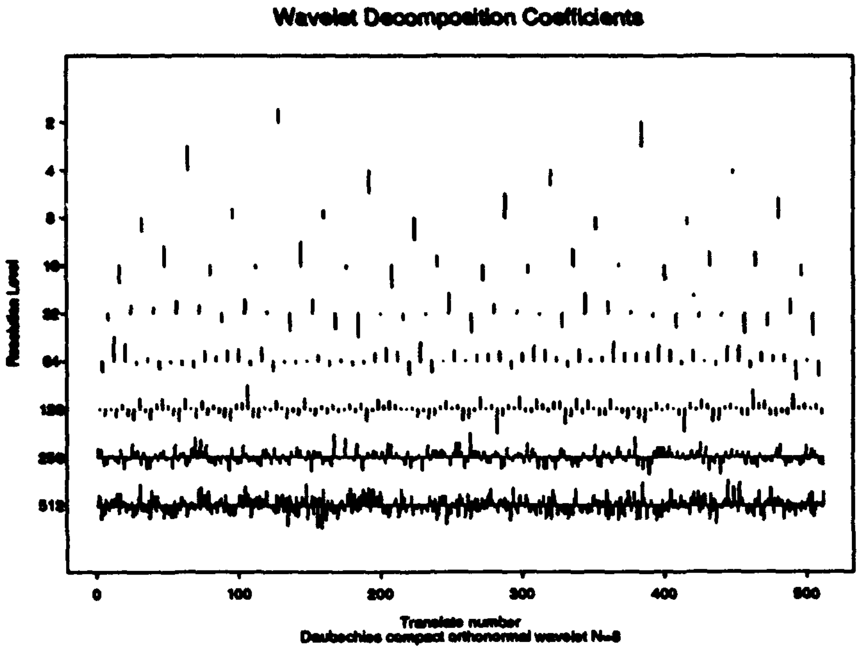

FIGURE 10. DAUBECHIES N=8 WAVELET COEFFICIENTS
FOR SIGNAL OF FIGURE 9

The aim is to prune some of the coefficients of the noisy signal, while the ultimate goal is the removal of those coefficients produced by the noise component of the signal. The hard thresholding approach of Donoho and Johnstone[5] is used here. In this approach, the variation of the coefficients is computed and a given coefficient d is kept if it satisfies

$$|d| \geq s\sqrt{2\log M} \tag{9}$$

where M is the number of wavelet coefficients. Thresholding can be applied to any number of levels.

The pruned coefficients from the sinusoidal signal are displayed in Figure 11. The pruning operator was applied across all the levels. As can be gleaned from Figure 11, the number of coefficients has decreased markedly.

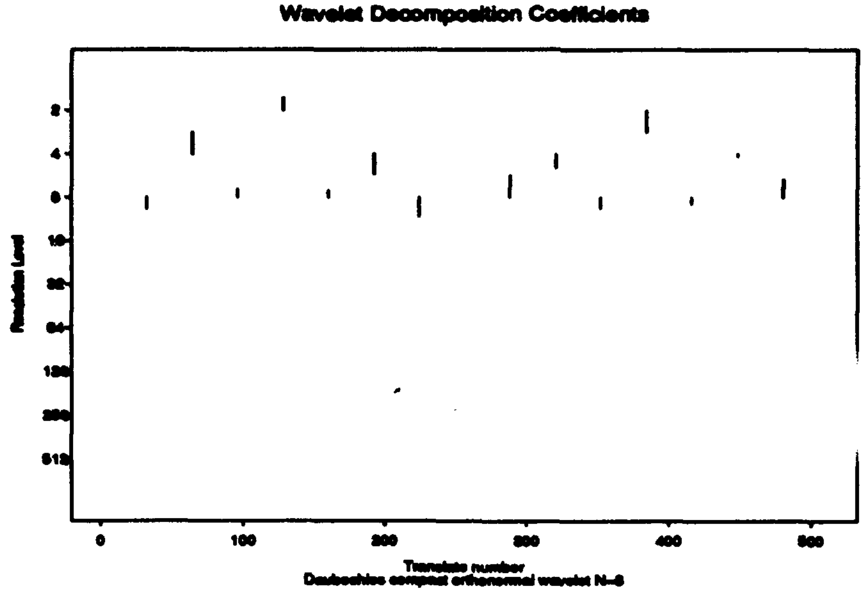

FIGURE 11. COEFFICIENTS AFTER PRUNING TECHNIQUES OF DONOHOE AND JOHNSTONE

The signal reconstructed from the pruned coefficients is plotted in Figure 12. As can be seen, the pruning process has removed a large component of the noise from the signal. In addition, the reconstruction process has faithfully reproduced the underlying structure of the data. This type of noise suppression technique or one of its variants would have application to the removal of battlefield transients, such as artillery blasts, from the helicopter signals.

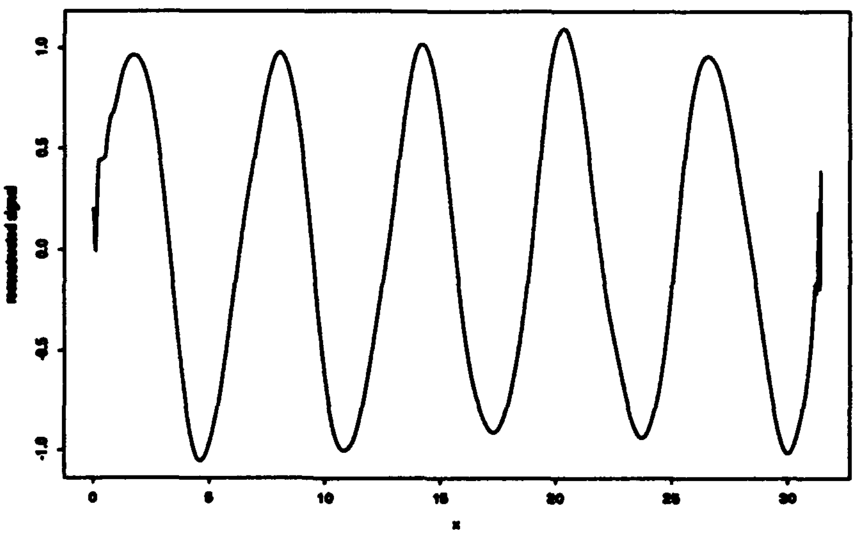

FIGURE 12. SIGNAL RECONSTRUCTED FROM PRUNED COEFFICIENTS

SYSTEM DESIGN CONSIDERATIONS

Before concluding, some of the system design and implementation issues will be considered. Some ideas will be presented as to how the WT can be used as part of a signal-processing suite, and appropriate hardware for its implementation will be discussed. The use of the WT for feature extraction and noise suppression has been demonstrated in the previous sections. The proposed classification system utilizes both of these capabilities, as illustrated in Figure 13.

After acquisition, the WT of the signal is performed using dedicated hardware, which will be discussed later. The signal is then reconstructed without transients and noise and passed to the harmogram analysis section. It must be noted that the WT section functions not only to *clean* the input signal but also to extract wavelet based features from the signal. These features are then fed to the classification section for fusion with the harmogram features. In the classifier section of the system, the WT and harmogram features are fused, and discriminant analysis is performed.

A good example of dedicated WT hardware is the AWARE Wavelet Transform Processor (WTP) chip. This device is capable of performing both the one- and two-dimensional wavelet transform in both the forward and inverse directions. This chip fully implements 2 (Harr), 4, and 6 coefficient transformations and can implement transformations requiring a longer supported wavelet via a cascading mechanism.[6] The chip operates at a clock speed of 30 MHz and has a reported execution speed of 33 nsec per transformed coefficient. This speed is fast enough to meet the requirements of most acoustic and image processing systems.

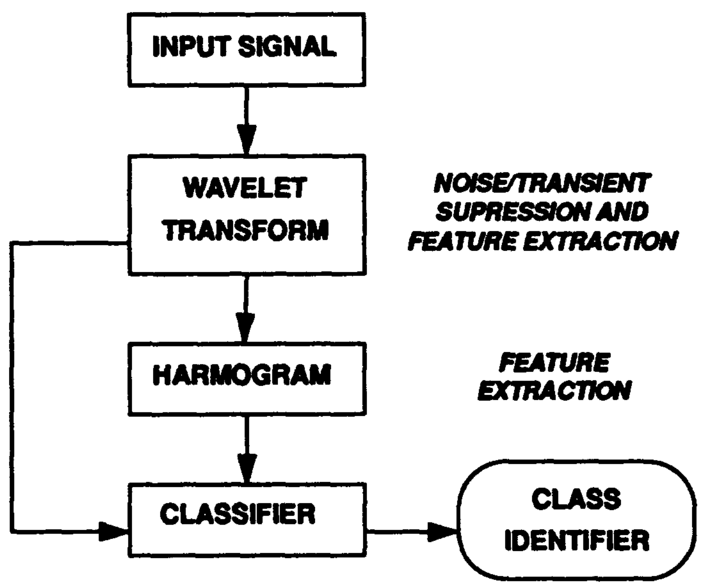

FIGURE 13. SYSTEM FLOWCHART

CONCLUSION

Some preliminary results have been provided that detail the application of the WT to acoustic signal classification. Whether the behavior of the wavelet features is a manifestation of the periodic component of the signal or an as-yet unidentified transient component will be the subject of investigations. Other future work will focus on the multiclass problem, the use of nonorthogonal wavelet bases, and alternate techniques for feature extraction. In addition, the transient suppression ability of the WT on field collected artillery blast data will be evaluated.

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13. ABSTRACT *(Maximum 200 words)*

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Block 5. Funding Numbers. To include contract and grant numbers; may include program element number(s), project number(s), task number(s), and work unit number(s). Use the following labels:

C	- Contract	PR	- Project
G	- Grant	TA	- Task
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